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FECUNDITY, FERTILITY AND THE FORMATION OF HUMAN CAPITAL*

Marc Klemp and Jacob Weisdorf

Exploiting a genealogy of English individuals living in the 16th to the 19th centuries, this study shows that lower parental reproductive capacity positively affected the socio-economic achievements of offspring. Using the time interval between the date of marriage and the first birth as a measure of reproductive capacity, we find that parental fecundity positively affected the number of siblings and that children of parents with lower fecundity were more likely to become literate and employed in skilled and high-income professions. This suggests there was a trade-off between child quantity and quality in England during the industrial revolution, supporting leading theories of the origins of modern economic growth.

Falling fertility rates and rising levels of human capital are central features of the centuries-long historical transition from economic stagnation to modern economic growth. Long-run growth theories have placed the trade-off between child quantity and child quality at the heart of this transition, arguing that technological progress incentivised parents to increase investment in their children's human capital by giving birth to fewer children (Galor and Weil, 2000; Galor, 2011).[1] Studies based on contemporary populations and inventive empirical strategies have generally not found clear-cut

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[1] The transition from stagnation to growth has been an intensive research topic in the growth literature in recent years (Galor and Weil, 1999, 2000; Galor and Moav, 2002; Hansen and Prescott, 2002; Lucas, 2002; Lagerlöf, 2003; Doepke, 2004; Galor, 2005; Strulik and Weisdorf, 2008; Voigtländer and Voth, 2009; O'Rourke *et al.*, 2013; Dalgaard and Strulik, 2015). The notion of a trade-off between the quantity and quality of offspring originated in the field of biology and found some of its first uses in economics by Becker (1960), Becker and Lewis (1973) and Becker and Tomes (1976).

empirical support for this idea.[2] The absence of strong evidence among modern populations could mean that the quality–quantity trade-off is negligible, or that it is inoperative in, for example, the presence of a welfare state.

In this article, we investigate the effect of parental fecundity (i.e. reproductive capacity) on the human capital of offspring. Furthermore, we develop a new empirical strategy, in which family size is instrumented by parental fecundity, and investigate the existence of a quantity–quality trade-off. England is a good setting for such an analysis. The costs of education were primarily borne by parents rather than the state, and family size varied more than in modern populations. Using a well-known individual-level genealogy, the Cambridge Group's family reconstitution data described in Wrigley *et al.* (1997), we first establish a negative effect of parental fecundity on offspring human capital and then present evidence in favour of a significant child quantity–quality trade-off.

Our empirical strategy relies on variation in the time span from a couple's marriage to their first birth, known as the protogenesic interval.[3] This interval mattered for two key reasons. First, women customarily continued to give birth up until the onset of age-related maternal sterility (Wrigley *et al.*, 1997). A prolonged protogenesic interval therefore decreased the remaining time available for reproduction, resulting in fewer births and thus smaller families. Second, couples with lower fecundity and hence longer protogenesic intervals have a lower monthly probability of conception. Couples with prolonged protogenesic intervals therefore tended also to have longer intervals between later births, which also spelled smaller families.

The length of the protogenesic interval is unrelated to the observed socio-economic conditions of the parents. This suggests that parents generally made no attempt to regulate the length of their protogenesic interval. Therefore, once we control for potentially confounding couple-specific biological determinants of fecundity, such as the parental marriage age, the length of the protogenesic interval contains a residual component that is as good as random.[4] This component allows us to use the protogenesic interval to identify the effect of exogenous variation in family size on offspring quality, thereby addressing the endogeneity problem involved in estimating the effect of family size on child quality.

We first employ a reduced-form approach, regressing a variety of measures of offspring quality on the parents' protogenesic interval, while controlling for a wide range

[2] Studies based on contemporary (i.e. 20th century) data include Leibowitz (1974); Rosenzweig and Wolpin (1980); Hanushek (1992); Black *et al.* (2005, 2010); Caceres (2006); Li *et al.* (2008); Rosenzweig and Zhang (2009); Angrist *et al.* (2010); Åslund and Grönqvist (2010); Millimet and Wang (2011); Aizer and Cunha (2012); Basso (2012); Lawson *et al.* (2012); Mogstad and Wiswall (2012); Ponczek and Souza (2012); Collins *et al.* (2014); Fitzsimons and Malde (2014); Jun and Lee (2014); Liu (2014, 2015); Peters *et al.* (2014); Abdul-Razak *et al.* (2015); Bougma *et al.* (2015); Dang and Rogers (2015); Doepke (2015); Huang (2015); Juhn *et al.* (2015); Dumas and Lefranc (2016); Huang *et al.* (2016); Lawson and Mulder (2016); Mogstad and Wiswall (2016); Ross *et al.* (2016); Azam and Saing (2017); Baranowska-Rataj *et al.* (2017); Brinch *et al.* (2017); Datar (2017); Fernihough (2017); Guo *et al.* (2017); Kugler and Kumar (2017); Li and Zhang (2017); Liang and Gibson (2017); Lin (2017); Palloni (2017); Qin *et al.* (2017); Zhang (2017).

[3] As will become apparent, neither intentional nor unintentional attempts to conceive before marriage are a threat to our identification strategy. Our only identifying assumption is that marriage marked the intention to conceive – as was the prevailing social norm.

[4] Given the repeating process of monthly reproductive cycles, the distribution of protogenesic intervals in a completely homogeneous population would resemble a geometric distribution.

of potentially confounding variables. These analyses show that a longer protogenesic interval was associated with fewer and better-educated children, suggesting that higher reproductive capacity resulted in lower child quality.[5] Moreover, by interacting the length of the protogenesic interval with parental earning possibilities, we find that the negative effect of reproductive capacity on offspring quality did not apply to families of higher socio-economic rank, as one could expect.

In the second part of our study, we assume that the effect of the length of the protogenesic interval on offspring quality operated via family size.[6] Using instrumental variable regression analysis, where completed fertility is instrumented by the length of the protogenesic interval, we find a statistically significant effect of family size on offspring human capital.[7] Our findings show that a two-year delay in the time to first conception, corresponding to a reduction in family size by one surviving offspring, increased the probabilities among offspring of acquiring literacy by 7.3 percentage points and a skilled profession by 7.9 percentage points. Furthermore, it increased the occupational wealth among offspring by 0.22 on a seven-point scale. The findings indicate that the chances of becoming literate and obtaining a skilled or high-income profession were considerably higher among those born to couples with low reproductive capacity. Moreover, the findings support the idea that a child quantity–quality trade-off was a central mechanism in the transition to modern economic growth.

1. Data and Main Variables

Our empirical investigation exploits information on individuals from a sample of 26 English parishes. The locations of the parishes are illustrated in Figure B1 in online Appendix B. The information was originally recorded in English church books for the period 1541–871. It was later transcribed by the Cambridge Group for the History of Population and Social Structure as documented in Wrigley *et al.* (1997).[8] The parishes were selected by the Cambridge Group on merit of data quality and have been shown to represent England as whole rather well (Wrigley *et al.*, 1997, 41ff). In addition to documenting the dates of baptisms, marriages, burials as well as the genealogy of

[5] These findings suggest that reproductive capacity may have played a vital role for human capital formation with potential ramifications for the composition of genetic traits in present societies (e.g. Galor and Moav, 2002).

[6] A subsequent study by Galor and Klemp (2016) also uses the protogenesic interval as a source of variation in fertility. A comparable, though different identification strategy is employed in Aguero and Marks (2008, 2011) and Jensen (2012), where failure to conceive a second child despite regular intercourse without contraception acts as an instrument for family size among modern populations. Also, previous related empirical analyses of data from contemporary economies have instrumented fertility by the occurrence of twin births or by the sex composition of the first births in the family (Black *et al.*, 2005; Rosenzweig and Zhang, 2009; Angrist *et al.*, 2010). These instruments are generally weak in the context of historical populations, where fertility rates were much higher than in contemporary societies. Furthermore, twin births can be a problematic instrument due to the direct effect of twinning on child quality (Rosenzweig and Zhang, 2009).

[7] This finding is consistent with conclusions based data from other countries using historical (i.e. pre-20th century) data (Becker *et al.*, 2010; Shiue, 2013; Lynch, 2016; Diebolt *et al.*, 2017).

[8] Table C1 in online Appendix C provides an example of a reconstituted family from the sample, displaying the available information about family individuals.

individuals, the data frequently contains information on occupation and literacy status, which we explore below.[9]

1.1. *Sample Limitation*

We focus on families in which the first child was conceived after the wedding, i.e. in which the protogenesic interval was at least 40 weeks long.[10] In order to avoid confounding the effects of parental mortality on family size and offspring human capital investments, we follow standard demographic procedures by restricting the sample to completed marriages in which both parents survived until the wife reached the age of 50 (Wrigley *et al.*, 1997, p. 359).[11] Because a missing birth or death date implies that the individual likely migrated between parishes (Souden, 1984), the restriction to completed marriages, which requires the wife's birth and death dates, also mitigates the possibility of births occurring outside the sampled parishes. Families with unobserved birth and death dates of the husband are excluded for the same reason. We further restrict the sample to offspring with known occupation or literacy status. These restrictions leave us with 1,517 individuals born between 1596 and 1843 and coming from 729 families.[12] The summary statistics are reported in Table C3 in online Appendix C. Figure 1 shows the distributions of offspring with known occupation and literacy status by their year of birth. Nine out of 10 individuals were born between 1684 and 1814, which includes the majority of the classic years of the industrial revolution.

1.2. *Main Variables*

Our first main analysis explores the effect of parental reproductive capacity on offspring human capital. The dependent variable is either literacy skills, occupational skills or occupational wealth. Below we explain how this information was inferred from

[9] Among the sampled individuals with known birth or baptism date, the date of birth is known in 13.2% of the cases. Given that almost all children were baptised within one month of birth (Midi Berry and Schofield, 1971), the date of birth of individuals with unknown birth date is estimated to be three weeks prior to the date of baptism. Likewise, among individuals in the sample with known death or burial dates, the date of death is known in 2.6% of the cases. Since burials usually took place within three days of death (Schofield, 1970), the date of death of individuals with unknown death date is estimated to be the burial date.

[10] The average time to ovulation is two weeks. Thus, in light of the 38-week gestation period, the average time from the onset of intercourse to the first birth in couples that conceive in the first cycle is 40 weeks. Table C2 in online Appendix C establishes that the qualitative conclusions are robust to the inclusion of families in which the first birth occurred in weeks 38–40. Moreover, while the protogenesic interval above the mentioned cut-offs are significantly associated with the number of children (see subsection 4.1), there is – reassuringly – no significant association when restricting the sample to protogenesic intervals below 38 weeks, indicating that protogenesic intervals below 38 weeks capture pre-nuptial conceptions for which the marriage date is endogenous, meaning that the prenuptial protogenesic interval is not indicative of either fecundity or exogenous variation in the time available for reproduction. Moreover, when restricting the sample to protogenesic intervals below 38 weeks in specifications analogous to those in Table 2, as a form of placebo test, there is reassuringly no association between the protogenesic interval and offspring human capital achievements.

[11] The results are robust to alternative cut-offs. For example, the estimates of the coefficients on the protogenesic interval in Table 2 remain virtually unchanged and statistically significant if a cut-off of 45 years is used. Likewise, the coefficients remain significant at the 5% level for literacy, the 10% level for occupational skills and the 1% level for occupational wealth if the cut-off is removed.

[12] In this sample, literacy is known for 1,248 individuals, working skills for 652 individuals and occupational wealth for 686 individuals.

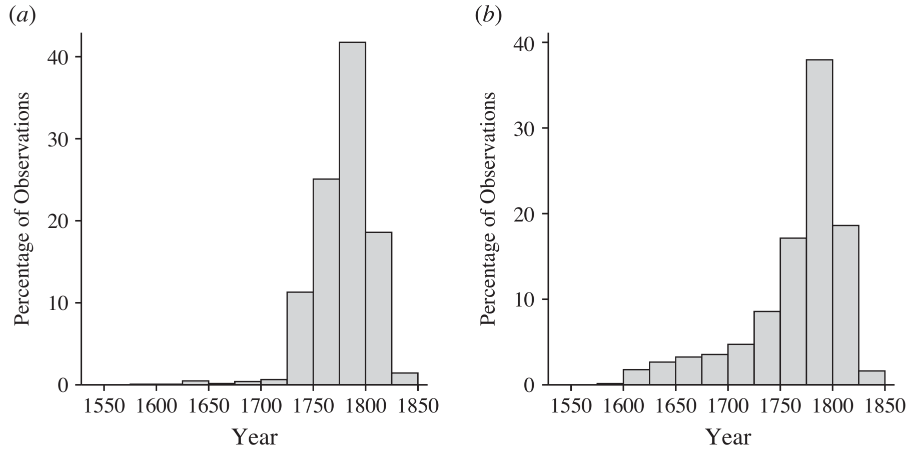

Fig. 1. *Histograms of Birth Dates for the Observations on Literacy and Occupation in the Total Regression Sample. (a) Observations in Literacy Sample. (b) Observations in Occupation Sample*

the original data. The main independent variable is the length of the protogenesic interval, i.e. the time span from the parents' marriage date to their first birth. Our second main analysis explores the potential mechanism through which the length of the protogenesic interval affects offspring human capital. This analysis uses the same dependent variables as in the first analysis, but the independent variable is the number of children surviving to age five, which we instrument by the length of the protogenesic interval.[13]

The idea is the following. If two couples had the same socio-economic characteristics, preference for offspring quality, etc., but differed in terms of reproductive capacity, then they would produce a different number of children.[14] A child quantity–quality trade-off would then imply that the children of the large family would end up with lower levels of human capital. Our analyses therefore control for variation in observed parental characteristics, including occupational and educational attainments and age at marriage. In order to account for differences in the local environment, including different costs of or returns to human capital, we also control for parish fixed effects and parish-specific occupational structures as explained below. This implicitly accounts for variations in living standards and other determinants of offspring human capital linked to different parish locations. Potential secular changes are controlled for by accounting for parental marriage time-period fixed effects.[15] The next subsections explain how the main dependent variables are derived.

[13] Table C4 in online Appendix C establishes that the results are robust to the inclusion of all births in the calculation of the family size rather than children surviving to age five.

[14] Evidence suggests that biological fertility affects completed family size even in modern populations. In particular, the time to the firstborn pregnancy has been found to predict family size in contemporary data (Joffe *et al.*, 2009).

[15] Table C5 in online Appendix C establishes that the results are robust to the inclusion of dummy variables indicating the time period in which the individual was born.

1.2.1. *Dependent variables*

Individual human capital is inferred from occupational titles and from the so-called signature literacy. Signature literacy comes from the signature (or lack thereof) on the marriage certificate: literate individuals would usually be able to sign their marriage certificate, while illiterate individuals could simply leave a mark. The absence of a signature is therefore an indication of illiteracy.

Occupational titles provide information about individual working skills and occupational wealth. To measure occupational skills, we employed the so-called HISCO and HISCLASS schemes (Leeuwen *et al.*, 2007; Leeuwen and Maas, 2011). These schemes divide the sampled individuals into skilled and unskilled workers based on the educational training required to conduct the work described by the occupational titles.[16] A standard two-step procedure was used. First, the occupational title was assigned the relevant five-digit code specified in the HISCO system. Then the code was entered into the HISCLASS system, which classifies the working skills using a two-dimensional score system based on the academic and vocational training needed to conduct the work.[17] For example, an English factory worker has the HISCO code number 99930, which according to the HISCLASS scheme designates an 'unskilled' profession.[18] HISCLASS does not appoint a skill level to individuals recorded as 'paupers' or 'gentry'. These specifications were therefore excluded from the skill sub-sample.[19]

To measure occupational wealth, we used the wealth classification proposed in Clark and Cummins (2010), which is based on the wealth-holdings of different occupational groups in early modern English wills. This classification splits occupations into seven groups in ascending order of wealth: labourers, husbandmen, craftsmen, traders, farmers, merchants and gentry. Our occupational wealth variable was then given the values 1 to 7 according to this ordering. 'Paupers' were placed in the same group as labourers.

Our three measures of human capital capture different variants of educational and occupational attainments and are not perfectly correlated. For literacy and occupational skills, the Pearson correlation coefficient is 40%; for literacy and occupational wealth it is 44%; and for occupational skills and occupational wealth it is 63%. All correlations are highly statistically significant ($p < 0.001$).

[16] The HISCO system is a historical extension of the International Standard Classification of Occupations (ISCO) managed by the International Labour Organization (ILO). The HISCLASS system is a historical extension of the Dictionary of Occupations (DOT) system, which gives scores for the requirements of skills of a wide range of occupations and which was originally created in the 20th century by the US Employment Service to match job seekers to jobs (Leeuwen and Maas, 2011).

[17] Using the earliest recorded occupations of the sampled individuals, more than 100 distinct occupational titles in the data were mapped into skilled and unskilled professions. However, 89% of the occupations were derived from marriage records or the earliest ecclesiastical event thereafter (typically the baptism of first-borns). Approximately, 7% of the occupations were derived from burial records, i.e. were recorded at the time of the individual's death. The remaining occupational titles (approximately 4%) were derived from an intermediate event, i.e. the baptism (or burial) of offspring of parity two or above.

[18] The occupational titles of our sample were coded using http://historyofwork.iisg.nl.

[19] As established in Table C6 in online Appendix C, the findings are robust to their inclusion on the assumption that paupers were unskilled and gentry skilled.

1.2.2. *Independent variables*

The key independent variable, i.e. the protogenesic interval, is discussed in further detail below. Here, we describe the control variables.[20]

First, we control for a number of variables concerning the parents. Since fecundity is affected by age, the age at marriage may have had a direct effect on the length of the protogenesic interval. Also, because it is negatively linked to the length of the post-wedding reproductive period, the age at marriage may also have influenced completed fertility. What is more, age at marriage was normally inversely related to wealth during this period (Wrigley *et al.*, 1997), so early marriages may be associated with higher offspring quality via an income channel. We thus account for marriage-age fixed effects by including age-group dummy variables indicating the age at marriage of the wife (five year intervals).[21]

We also account for educational and occupational heterogeneities by controlling for the same measures of parental human capital as those of their offspring.[22] Specifically, literate parents may have had higher income, which enabled them to support larger families. Literacy could also be taught by parents, potentially reducing the cost of endowing their offspring with literacy. Similarly, skilled parents potentially faced lower costs of endowing their offspring with skills compared to unskilled parents, and high-wealth fathers could afford both larger families and to devote more resources to their offspring. Since occupational wealth and skills are both based on occupational titles, paternal occupational wealth is divided into two main categories, with labourers and husbandmen making up the poorest segments of the English society.[23] Dummy variables indicating paternal literacy and occupational skills and wealth are therefore included.[24]

We also control for a number of variables concerning the sampled offspring. First, many studies have linked birth order to human-capital achievements (Ejrnæs and Pörtner, 2004; Black *et al.*, 2005; Klemp *et al.*, 2013). We thus include dummies for the birth order of offspring.[25]

We also use a dummy variable indicating offspring gender. This captures the fact that parents at the time were more likely to invest more in male offspring (Klemp *et al.*, 2013). Also, although the Prayer Books of the English Church prescribed that baptisms took place on Sundays, many of the recorded families did not comply with this rule. Non-Sunday baptisms, which we capture using a dummy variable, were possible for an additional fee, suggesting that a non-Sunday baptism service was indicative of the level of family income.[26]

[20] A more detailed explanation of the variables can be found in section A.1 in online Appendix A.

[21] The results are robust to controlling for the paternal age at marriage (Table C7 and Table C8.)

[22] The parental human capital control variables enter as dummy variables. This allows us to include families with unobserved parental human capital, captured by a dummy variable indicating missing information.

[23] Table C9 in online Appendix C establishes that the results are robust to the inclusion of dummies for all seven paternal wealth groups.

[24] Given the low female labour participation rate, information on maternal occupational wealth is omitted.

[25] Online Appendix C, Table C10 shows that the findings are robust to excluding these dummies, as well as to controlling for birth-order effects in other ways. The table also establishes that controlling for birth order is the most conservative approach.

[26] The fact that non-Sunday baptisms were often requested by affluent families is supported by the positive associations between a non-Sunday baptism and the number of surviving siblings as well as their level of human capital, findings which we establish in the regression analyses below.

Moreover, different occupational structures may have affected local premiums to education and hence parents' decisions about how much to invest in offspring human capital. Different occupational structures could also have influenced parental fecundities (see e.g. Juul *et al.*, 1999, for related evidence on this for modern populations). The sampled parishes range from market towns to remote rural villages and have been organised by Schofield (2005) into four categories: 'agriculture', 'industry', 'retail and handicraft' and 'other' (a mix). Dummies capturing the four different categories of parishes are therefore included in the specifications.[27]

Finally, fecundity and human capital formation have possibly been affected by time-period specific factors, such as a changing social or technological environment. We thus control for marriage time-period fixed effects in the form of dummy variables indicating the time-period of marriage of the parents (20-year intervals).[28]

2. Empirical Strategy

2.1. *Introduction to the Empirical Strategy*

The identification of a causal effect of parental fertility (offspring quantity) on the human capital of children (offspring quality) is affected by two potential econometric issues: omitted variable bias and reverse causality. Omitted variable bias occurs if correlates of both offspring quantity and quality are not controlled for. For example, wealthier parents are able to both provide for more offspring and to finance higher offspring quality. Failing to account for parental wealth, or other confounding factors, may thus tend to obscure a quantity–quality trade-off.[29] Reverse causality occurs if the offspring's quality affects their quantity. For example, lower offspring quality could lead to lower survival probability, which could increase completed fertility via child replacements. This would tend to generate a negative correlation between the quantity and quality of offspring that is unrelated to a quantity–quality trade-off.

Our empirical strategy addresses both these issues by focusing on parental fecundity rather than fertility. We use the fact that fecundity is primarily (if not exclusively) influenced by biological factors (such as age) rather than socio-economic factors. The protogenesic interval is a standard measure of parental fecundity in the fields of historical demography and medicine and is used to estimate the reproductive capacity of historical populations (Bongaarts, 1975; Woods 1994; Olsen and Andersen, 1999). Since the length of the protogenesic interval is randomised, we use the couple-specific time interval to estimate the effect of fecundity on child quality.[30]

[27] Table C11 in online Appendix C demonstrates that the results are robust to controlling for parish-level fixed effects.

[28] The results are robust to accounting for marriage year (i.e. one-year interval) fixed effects (see Table C12 in online Appendix C).

[29] Indeed, in the time period under investigation, wealthier parents both gave birth to more children and produced better educated offspring. See e.g. Boberg-Fazlic *et al.* (2011); Clark and Hamilton (2006); Leunig *et al.* (2011).

[30] While the present study (and an earlier working paper which forms the basis for the current article, i.e., Klemp and Weisdorf, 2011) is, to our knowledge, the first to investigate the effects of the protogenesic interval on family size, offspring literacy and occupation in adulthood, studies using data for modern populations have investigated the related phenomenon of the associations between time to pregnancy (i.e. the time from

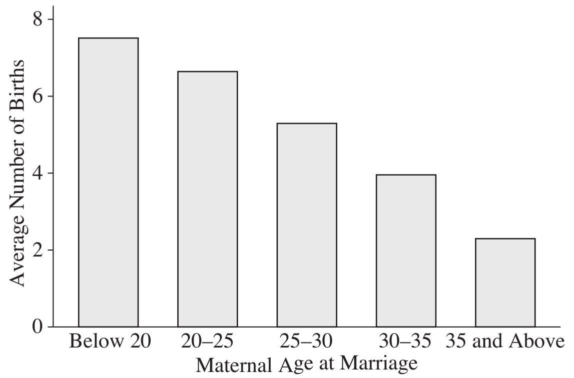

Fig. 2. *Number of Births by the Mother's Age at Marriage among 4,582 Families in the Data in Which Both Parents Survived to the Date at Which the Mother Turned 50*

The length of the sampled protogenesic intervals has a large effect on the completed fertility of our couples. The large size of the effect is likely related to the fact that married women in early modern England typically continued to give birth until age-related sterility set in, usually after the age of 40 (Wrigley *et al.*, 1997). Because premarital sex was seen as an immoral act by the Church of England, and by English society as a whole, the postponement of marriage was a key means of fertility limitation in this period.[31]

The sampled women produced around five surviving children on average.[32] Figure 2 shows the strong correlation between the wife's age at marriage and her total number of births. A longer protogenesic interval has a similar effect to that of a delayed marriage

the intention to conceive until pregnancy) and the birth-related outcomes of the particular birth resulting from the pregnancy. Some of these studies have found that increased time to pregnancy is associated with adverse birth outcomes such as miscarriage, preterm delivery, caesarean delivery, neonatal death, extra-uterine pregnancies, low Apgar score, low umbilical vein pH or the need for neonatal intensive care (Joffe and Li, 1994; Henriksen *et al.*, 1997; Basso and Baird, 2003; Axmon and Hagmar, 2005; Basso and Olsen, 2005; Raatikainen *et al.*, 2010). Meanwhile, other studies have found that time to pregnancy is not related to some of these, as well as other, outcomes, including preterm delivery, small-for-gestational-age, sex ratio and birthweight (Joffe and Li, 1994; Cooney *et al.*, 2006; Joffe *et al.*, 2007). It is important to note that a possible adverse effect of time to pregnancy on the birth outcome of the particular birth will presumably bias against finding a positive effect of the protogenesic interval on offspring education when the first birth is included in the sample. Nevertheless, we find strong positive effects of the protogenesic interval on offspring quality in adulthood across all siblings no matter if we control for birth order fixed effects or not. Furthermore, we find that the estimated effects of the protogenesic interval is not significantly different if the sample is restricted to birth orders above one.

[31] In fact, one reason why English upper-class couples had more births than their lower-class counterparts was because of their lower maternal marriage ages (Boberg-Fazlic *et al.*, 2011). Birth control was, however, practised not only by means of regulating the wife's age at marriage but also within marriage by sexual abstinence, *coitus interruptus* and extended breastfeeding (McLaren, 1978; Santow, 1995). Using an extended sample of the present data, Cinnirella *et al.* (2017) have found that pre-modern couples practised birth spacing by, for example, increasing the time elapsed between two births when real wages fell. Importantly, their estimates suggest that the protogenesic interval was not associated with variations in living standards.

[32] See Table C3 in online Appendix C. Based on a less restricted sample of married women in the 18th century, which includes also those who died before the age of 50, the average number of total births was five (Wrigley *et al.*, 1997).

Fig. 3. *The Histogram Depicts the Durations (per Two-week Interval) from Marriages to First Marital Births of 38,914 Couples in England from the 16th to the 19th Century Who Gave Birth between the First and the 260th Week of Their Marriage Date*

by reducing the time available for reproduction. We show below that the protogenesic intervals are moreover positively correlated with later birth intervals corroborating the notion that the protogenesic interval reflects the level of fecundity and suggests that it is therefore associated with a further reduction in the number of births within a woman's reproductive period.

Figure 3 suggests that marriage normally signified a deliberate attempt to start a family.[33] A sharp spike in births occurs starting 34 weeks after marriage. A quarter of all births thereafter happened within the 36th and the 44th week.[34] General adherence to the social and religious norms at the time is partly reflected in the fact that premarital conception was uncommon.[35] Three quarters of the first births occurred after 35 weeks

[33] The fact that some couples had unprotected intercourse before their marriage will not affect the validity of the empirical strategy given that the probability of a pregnancy, and thus the length of protogenesic interval, is generally unaffected by past sexual activity not leading to pregnancy. As we are focusing on first births conceived after marriage, and since conception is assumed to be an approximately memoryless process, the protogenesic interval should remain unaffected by pre-marital sex.

[34] Full-term children are born after 38 weeks of gestation. However, since marriage may not coincide with the ovulation period, children born between weeks 36 and 44 are considered at term.

[35] Child births before marriage are not part of our sample. Some studies, such as Wyatt (1992), have argued that children born out of wedlock in areas where the industrial revolution first emerged (i.e. Cheshire) made up almost 10% of all births. Since bastardy and pre-nuptial pregnancies were supposedly more prevalent among the poor, and because we find that the effect of the protogenesic interval is larger among the lower socio-economic ranks, including children born outside of marriage might reinforce our results.

of marriage. With premature births in mind, this suggests that an even larger fraction of first-borns was conceived after marriage.[36]

2.2. *The Protogenesic Interval*

We now explore the underlying characteristics and determinants of the key independent variable: the length of the protogenesic intervals. We establish:

(*i*) that the protogenesic interval is a meaningful proxy for parental fecundity;
(*ii*) that the protogenesic interval is unaffected by potentially confounding factors observed in our data, such as parental socio-economic characteristics including skills and wealth;
(*iii*) that studies of modern data also suggest that the protogenesic interval is not affected by unobserved confounding factors; and
(*iv*) that the distribution of our protogenesic intervals is comparable to that of a contemporary population in which the time from the onset of regular unprotected intercourse to conception is studied and documented.

2.2.1. *The distribution of the protogenesic interval and its relation to fecundity*

Imagine a population consisting of equally-fecund couples who have unprotected sexual intercourse on a regular and identical basis. Despite identical levels of fecundity, these couples will have widely different times to conception. Indeed, in such a homogeneous population, the protogenesic intervals would follow a geometric distribution. Fecundity is measured by fecundability – the probability of achieving conception in a given monthly cycle (Gini, 1924). If $p \in (0, 1)$ denotes fecundability, then, in light of the geometric distribution of the time to conception, the coefficient of variation of the time to conception will be $p^{-1/2} > 1$. With a monthly probability of conception of 10%, the standard deviation of the time to conception in a homogeneous population will therefore be more than 3.16 times the average time to conception.

In a heterogeneous population, the proportion of the variance that can be attributed to differences in fecundity depends on the variation in fecundability between more and less fecund individuals. With small differences in fecundability, only a small proportion of the variance can be attributed to differences in fecundity. If half the population has a fecundability of 17% per monthly cycle and the other half has a fecundability of 15% per cycle, then simulations show that less than 0.5% of the variance can be attributed to the difference in fecundity between the two groups. However, if the fecundability of the less fecund group drops to 5% per cycle, then almost 20% of the variance in time to conception can be attributed to differences in fecundity.

[36] It should be noted that the fraction of births occurring after 35 weeks is larger in the Canadian province of Quebec in the period between the 17th and the 18th century (Galor and Klemp, 2016), possibly due to an increased prevalence of pre-marital conceptions in England after the 18th century. The results are robust towards excluding this later period. It should also be noted that, in the complete dataset including 41,238 mothers, less than 2% of all births occurred prior to the marriage date, whereas 3.6% of the births occurred after five years of marriage. Finally, it should be noted that the small hump in the histogram around weeks 11 to 16 could reflect the sum of the typical time from conception to the realisation that the woman is pregnant and the typical time to arrange a 'shotgun' wedding.

As we demonstrate in subsection 2.2.4, the sampled fecundability ranges from 6% to 17% per monthly cycle for conceptions in the first year of marriage. Therefore, although variation in the length of protogenesic intervals is largely random, a non-trivial share of it can be attributed to differences in fecundity between couples.

2.2.2. *Determinants of time to pregnancy in modern populations*

Studies using data for modern populations have found that time to pregnancy is primarily determined by purely biological factors (e.g. age, menstrual cycle length, parity or the degree of oxidative damage to sperm DNA) (Schwartz and Mayaux, 1982; Juul *et al.*, 1999; Loft *et al.*, 2003; Axmon *et al.*, 2006; Ecochard, 2006; Wise *et al.*, 2011). Moreover, those factors that correlate with fecundity have very little predictive power for determining the time to pregnancy. Axmon *et al.* (2006, p. 1279), although they had information on a large variety of factors, conclude that their multivariate model 'explained only a small fraction of the variation in the observed time to pregnancies'. This is consistent with the literature review in Ecochard (2006, p. 142), which states that 'most of the biological heterogeneity' in fecundity 'remains unexplained'. At any rate, biological determinants of variations in fecundity are of no concern with respect to our identification strategy, because our interest regards the effect of the inherent biological nature of fecundity on offspring quality as well as its potential effect via fertility.

Other factors sometimes found to influence fecundity include exposure to chemicals. The most robust findings relate to pesticides (de Cock *et al.*, 1994; Curtis *et al.*, 1999; Cohn *et al.*, 2003; Axmon *et al.*, 2006), but even these findings are ambiguous. Curtis *et al.* (1999, p. 112) argue that pesticides may potentially affect fecundity, however, they still found 'no strong or consistent pattern of associations of pesticide exposure with time to pregnancy'. Other environmental exposures are even less likely to influence the time to pregnancy. For example, Joffe *et al.* (2003) found no effect of lead exposure on the time to pregnancy. Regardless, chemical factors are not a concern here, because humans were not usually highly exposed to potentially problematic chemicals in the time period of our study.

Lifestyle-related and socio-economic factors are generally found not to determine the time to pregnancy. Juul *et al.* (1999) found that smoking, body mass index, age and parity did not explain regional differences in fecundity in their data, and Juhl *et al.* (2001) found no association between moderate alcohol intake and fecundity. Joffe and Barnes (2000) concluded that a wide range of socio-economic characteristics did not affect the time to pregnancy of the first birth among the subsequent generation. Characteristics included body-mass index, height, smoking habits and social class. The lack of intergenerational effects is interesting here because it suggests that grand-parental socio-economic characteristics are unrelated to parental time to pregnancy.[37]

The key message from the medical literature is that fecundity is determined by biological components and much less so by lifestyle or socio-economic circumstances.

[37] This view is consistent with Aguero and Marks (2008, 2011) who show that infertility is largely unrelated to parental characteristics, besides age, concluding that according to their analysis, 'infertility is not correlated with "predetermined" or background characteristics of women' (Aguero and Marks, 2011, p. 806).

Table 1

The Association between the Protogenesic Interval (PI) and Observed Socio-economic Characteristics

	Years to first birth					
	(1)	(2)	(3)	(4)	(5)	(6)
Age of marriage of mother (years)	0.065***					0.066***
	(0.023)					(0.023)
Age of marriage of mother (years) squared	−0.001***					−0.001***
	(0.000)					(0.000)
Poor father		−0.038				−0.026
		(0.052)				(0.064)
Skilled father			0.027			−0.004
			(0.063)			(0.077)
Skilled mother			0.356			0.343
			(0.234)			(0.235)
Literate father				0.088		0.085
				(0.074)		(0.078)
Literate mother				−0.078		−0.107
				(0.084)		(0.084)
Retail location					0.057	0.060
					(0.050)	(0.052)
Industrial location					0.067	0.082
					(0.052)	(0.053)
Agricultural location					−0.059	−0.045
					(0.044)	(0.048)
No. of observations	3,003	3,003	3,003	3,003	3,003	3,003

Notes. This table presents the results of a series of Cox proportional hazard regressions analyses of the time to first birth on various observable parental and locational characteristics. The estimates are log hazard ratios and larger coefficients correspond to a higher risk of birth (i.e. shorter protogenesic interval). All regressions account for parental marriage time-period fixed effects and includes dummies, indicating unknown information. The coefficient on a constant term is omitted from the table. Standard errors clustered on the parental marriage year level are reported in parentheses. ***Significant at the 1% level. **Significant at the 5% level. *Significant at the 10% level.

Axmon *et al.* (2006, p. 1279) concluded that 'female biological factors seemed more important predictors of [time to pregnancy] than lifestyle factors'. Consistent with these findings, we show below that the observed socio-economic variables in our data have no statistical explanatory power over the length of their protogenesic intervals. Thus, while the possibility of omitted variables can never be entirely ruled out, the limited scope for lifestyle-related and other potentially omitted variables in explaining parental fecundity is reassuring for our analyses.

2.2.3. *The protogenesic interval and observed socio-economic variables*

We now investigate the correlation between the length of the protogenesic interval and our observed variables. This helps provide an indirect assessment of the exogeneity of the protogenesic interval after we control for parental-specific biological factors. Table 1 shows the results of running Cox proportional hazards duration models on a sample of 3,003 families.[38] These estimations include the entire set of family and parish-level variables described above and used in our main analyses below.

The Cox model assumes that:

$$\eta(t) = \eta_0(t)\exp(\mathbf{x}'\boldsymbol{\beta}),$$

where $\eta(t)$ is the hazard of the outcome event at time t; $\eta_0(t)$ is a baseline, unspecified, hazard function; and $\mathbf{x}$ is a vector of family and parish-level explanatory variables. The outcome event is the date of the first birth, and time zero is the marriage of the couple. Positive coefficients indicate an increased probability of birth, meaning shorter protogenesic intervals.

The results presented in Table 1 suggest a complete absence of significant correlations between the length of the protogenesic interval and observed socio-economic characteristics of the parents, except the maternal age. The lack of a significant correlation is crucial, because it suggests that the protogenesic interval is not correlated with key parental socio-economic characteristics that could potentially co-determine offspring human capital, including parental literacy, skills and wealth. Ignoring statistical significance, the estimated correlations indicate a negative correlation between the parents' socio-economic status and the length of the protogenesic interval. This would imply a bias (if any) against finding a positive association between the protogenesic interval and offspring human capital, and hence against finding a child quantity–quality trade-off.

The only significant variables in the regression analysis above are the maternal marriage age and its square. According to the estimates in the full specification in column (6), the peak fecundity is estimated to occur at 27.3 years of age. Table 1 thus confirms a well-established non-monotonic association between age and fecundity: a woman's fecundity first gradually increases and then starts to decline around age 25–30 (see e.g. Eijkemans *et al.*, 2014, and references therein). Our main analysis therefore controls for age-related differences in parental fecundity.

2.2.4. *Historical and contemporary distributions of the protogenesic interval*

In order to further validate our empirical strategy, we compare the distribution of the protogenesic intervals in our data to those of a group of newly-wed Muslim couples in rural Palestine, documented by Issa *et al.* (2010). There are two main reasons why the Palestinian data is appropriate for this comparison. First, there were strong religious and social norms against having intercourse before the day of the wedding both in the Palestinian population and in historical England. Issa *et al.* found no evidence of pre-marital pregnancies or even co-habitation among their sampled cou-

[38] Since offspring human capital is not needed for this assessment, we do not have to constrain the sample to completed marriages but can use a larger sample instead, thus increasing the statistical power. If we restrict the sample to the 729 completed marriages of our main regression samples below, then the results are similar, except that the first and second-order effects of maternal marriage age become insignificant, and the effect of maternal skills becomes negative and significant. The latter finding may be caused by the small number of skilled mothers (i.e. seven out of 729), who may not be representative. Also, even if we take this effect at face value, then it biases against finding a trade-off effect. However, the 'skilled mother' variable becomes insignificant in the 729 family sample when we use a Bonferroni correction for the multiple comparisons problem.

ples. Second, the declared intention among the Palestinians was to become pregnant on the day of the wedding or as soon as possible thereafter. All couples reported that their wedding night marked the onset of unprotected sex, after which intercourse occurred frequently up until the time of pregnancy. Specifically, 16% of the Palestinian couples reported having had sexual intercourse between one and six times per week, while 73% reported having had intercourse more than seven times weekly.[39]

Any tendency, intentional or not, among our English couples to delay their first birth after marriage would supposedly result in a lower frequency of births following marriage compared to the Palestinian couples. However, we do not find this to be the case. The English couples were actually slightly more likely to achieve pregnancy within one year of marriage compared to the Palestinian couples.[40] The chances of conception in the most relevant Palestinian control group (women with less than 10 years of schooling) were 12% after one month; 64% after six months; and 76% after 12 months. The English numbers were 17% after one month; 57% after six months; and 77% after 12 months. The implied average monthly probability of conception for the Palestinians was 12% in months 0–1; 11% in months 2–6; and 5% in months 6–12. The English implied probabilities were 17% in months 0–1; 10% in months 2–6; and 6% in months 6–12.[41] The similar distributions suggest that marriage in early modern England did indeed mark the onset of unprotected intercourse with no apparent delay of post-marital pregnancies.[42]

3. The Protogenesic Interval and Offspring Human Capital

3.1. *Econometric Specification*

We now turn to our two main analyses. The first assesses the effect of the length of the protogenesic interval on the offspring's human capital attainments later in life. To this end, we estimate a series of models of the following form:

$$h_{ij} = \beta_0 + \beta_1 p_j + \mathbf{a}'_{ij}\boldsymbol{\beta}_2 + \mathbf{b}'_j\boldsymbol{\beta}_3 + \varepsilon_{ij}, \tag{1}$$

where h_{ij} is a measure of human capital (i.e. signature literacy, occupational skills, or occupational wealth) of individual i in family j; p_j is the length of the protogenesic interval in family j; $\mathbf{a}_{ij}$ is a vector of individual-level control variables; $\mathbf{b}_j$ is a vector of family and parish-level control variables for family j; and ε_{ij} is an error term that is correlated within families.[43]

[39] The remaining 11% refused to disclose the frequency of their sexual activity.

[40] Note also that the pregnancies in our sample all led to live births; this was not necessarily the case among the Palestinians.

[41] The fact that the probability of conception is lower for couples with longer protogenesic intervals supports the notion that the protogenesic interval does indeed proxy for parental fecundity.

[42] See also Stone (1977).

[43] We examine the robustness of the estimates to different sets of control variables. We refer to 'Baseline Controls' as variables indicating gender, paternal poor status, non-Sunday baptism and parish type, we refer to 'Parental Skills' as variables indicating paternal and maternal skills, and we refer to 'Parental Literacy' as variables indicating paternal and maternal literacy. We always include dummies indicating unknown information when relevant.

3.2. *Results*

The baseline OLS estimates are presented in Table 2. Here, we account for age at marriage, year of marriage, parental occupational skills and literacy status, paternal wealth, parish location and offspring gender and birth order. Table 2 shows a highly statistically significant and negative association between parental fecundity, measured by the length of the protogenesic interval, and the human capital of the offspring, both before and after we account for parish-level fixed effects, gender, parental literacy, parental skills, paternal occupational poor status and non-Sunday baptism.[44] Using all of our baseline control variables, an increase in the protogenesic interval by one year results in a 3.2 percentage points higher probability of the offspring being literate (column (3)); a 3.8 percentage points higher probability of holding a skilled occupation (column (6)); and a 0.11 point higher score on the occupational wealth scale (column (9)).[45]

3.3. *Heterogeneous Effects*

We now investigate how these effects vary with the socio-economic characteristics of families. We are particularly interested in establishing whether or not the effects of fecundity on child quality was smaller for literate and skilled parents, whom we could describe as members of a socio-economic elite. We hypothesise that the effects were smaller for these families since they could better afford to increase their investments in offspring human capital in the case of additional children.

To find out, we include an interaction term between the protogenesic interval and a combined indicator of parental skills and wealth, while including each variable separately as well. Offspring of the socio-economic elite, defined as having a literate and skilled father, make up slightly less than one-fifth of all sampled children and around half of all children from families with reported paternal literacy and skills. The results are presented in Table 3, which includes the same control variables as Table 2 above.[46]

Table 3 confirms the hypothesis that the positive effect on offspring quality of the protogenesic interval is smaller for the socio-economic elite. The combined coefficients for this group are closer to zero and statistically insignificant. This suggests that the socio-economic elite was able to offset otherwise negative impacts of their fecundity on investments in their offspring's quality.[47]

The fact that the effects on skills and wealth were smaller for elite than for non-elite families suggests that even larger effects apply to non-elite families than for

[44] At first glance, the finding that males were less likely to achieve a skilled occupation (columns (4)–(6)) may appear surprising. However, unskilled work was physically very demanding, explaining why working women were usually engaged in skilled work instead (notably spinning and weaving).

[45] Online Appendix C, Table C13, shows that our results are robust to the use of logistic regression analyses instead of OLS.

[46] We classify families with unreported paternal literacy or skills as non-elite (see section A.2 in online Appendix A). Table C14 in online Appendix C examines the robustness of the results to controlling for unknown information on paternal literacy or occupational skills as well as to accounting for long protogenesic intervals.

[47] The fact that the effect on literacy does not differ statistically significantly for the socio-economic elite in columns (2) and (3) could indicate that the socio-economic elite were less focused on offsetting the detrimental effects on literacy.

Table 2

The Effect of the Length of Protogenesic Interval (PI) on the Human Capital of Offspring

	Literacy			Skilled occupation			Occupational wealth		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Years to first birth	0.032***	0.032**	0.032***	0.040***	0.039***	0.038***	0.119***	0.120***	0.113***
	(0.012)	(0.012)	(0.011)	(0.014)	(0.013)	(0.013)	(0.042)	(0.041)	(0.041)
Male	0.098***	0.101***	0.109***	−0.288***	−0.287***	−0.280***	0.387**	0.387**	0.384**
	(0.028)	(0.028)	(0.027)	(0.069)	(0.071)	(0.073)	(0.179)	(0.178)	(0.187)
Non-Sunday baptism	0.095***	0.098***	0.070**	0.116***	0.113***	0.113***	0.280**	0.257**	0.225*
	(0.030)	(0.030)	(0.030)	(0.038)	(0.037)	(0.037)	(0.117)	(0.118)	(0.120)
Poor father	−0.387***	−0.306***	−0.203***	−0.398***	−0.260***	−0.246***	−1.585***	−1.396***	−1.258***
	(0.043)	(0.056)	(0.057)	(0.044)	(0.055)	(0.054)	(0.153)	(0.171)	(0.165)
Skilled father		0.147**	0.094		0.227***	0.214***		0.296*	0.206
		(0.063)	(0.063)		(0.068)	(0.068)		(0.169)	(0.162)
Skilled mother		0.306	0.370*		0.828***	0.795***		2.569**	2.475**
		(0.213)	(0.212)		(0.222)	(0.226)		(1.029)	(1.011)
Literate father			0.191***			0.058			0.471***
			(0.048)			(0.060)			(0.178)
Literate mother			0.208***			0.029			0.293
			(0.048)			(0.062)			(0.226)
Agricultural location	0.093*	0.089*	0.092*	−0.064	−0.088	−0.105*	−0.123	−0.178	−0.213
	(0.051)	(0.050)	(0.052)	(0.065)	(0.059)	(0.061)	(0.194)	(0.160)	(0.166)
Industrial location	0.127**	0.107**	0.106**	0.329***	0.273***	0.250***	−0.303	−0.361*	−0.439**
	(0.052)	(0.052)	(0.051)	(0.062)	(0.059)	(0.060)	(0.210)	(0.208)	(0.203)
Retail location	0.196***	0.196***	0.142**	0.034	0.024	0.013	−0.102	−0.091	−0.112
	(0.060)	(0.059)	(0.061)	(0.050)	(0.051)	(0.052)	(0.165)	(0.169)	(0.170)
R^2	0.161	0.171	0.225	0.279	0.320	0.329	0.311	0.333	0.355
No. of observations	1,248	1,248	1,248	652	652	652	686	686	686
No. of families	571	571	571	453	453	453	468	468	468

Notes. This table presents the results of a series of OLS regression analyses of measures of human capital achievements on the time to first birth (protogenesic interval) in the family. All regressions account for parental marriage time-period fixed effects, maternal marriage age interval fixed effects, birth order fixed effects and dummies indicating unknown information. The coefficient on a constant term is omitted from the table. Standard errors clustered on the family level are reported in parentheses. *** Significant at the 1% level. ** Significant at the 5% level. * Significant at the 10% level.

Table 3

Heterogeneity of the Effect of the Length of the Protogenesic Interval (PI) on Offspring Human Capital

	Literacy			Skilled occupation			Occupational wealth		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Years to first birth	0.045***	0.044***	0.039***	0.056***	0.054***	0.055***	0.162***	0.164***	0.161***
	(0.015)	(0.015)	(0.014)	(0.017)	(0.016)	(0.016)	(0.050)	(0.048)	(0.048)
Years to first birth × literate and skilled father	−0.043**	−0.039*	−0.030	−0.066**	−0.061**	−0.064**	−0.204**	−0.194*	−0.200**
	(0.021)	(0.022)	(0.021)	(0.028)	(0.027)	(0.026)	(0.100)	(0.099)	(0.099)
Literate and skilled father	0.248***	0.226***	0.025	0.269***	0.204***	0.170*	0.890***	0.856***	0.495
	(0.062)	(0.070)	(0.086)	(0.065)	(0.066)	(0.093)	(0.254)	(0.262)	(0.335)
Skilled father		0.063	0.100		0.183***	0.189***		0.098	0.150
		(0.072)	(0.070)		(0.070)	(0.071)		(0.168)	(0.166)
Literate father			0.198***			0.020			0.373*
			(0.057)			(0.077)			(0.224)
Baseline controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Parental skills	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Parental literacy	No	No	Yes	No	No	Yes	No	No	Yes
Signif. of sum of interaction terms	0.878	0.783	0.604	0.622	0.750	0.662	0.631	0.732	0.650
R^2	0.176	0.181	0.226	0.296	0.328	0.334	0.328	0.347	0.359
No. of observations	1,248	1,248	1,248	652	652	652	686	686	686
No. of families	571	571	571	453	453	453	468	468	468

Notes. This table presents the results of a series of OLS regression analyses of measures of human capital achievements on the time to first birth (i.e. protogenesic interval) in the family and its interaction with a dummy variable indicating if the father of the family was both literate and had a skilled profession. Except for including the interaction term and the dummy variable itself, the specifications correspond to those of the corresponding columns of Table 2, omitting the estimated coefficients on control variables due to space concerns. All regressions account for parental marriage time-period fixed effects, maternal marriage age interval fixed effects, birth order fixed effects and dummies indicating unknown information. The coefficient on a constant term is omitted from the table. Standard errors clustered on the family level are reported in parentheses. *** Significant at the 1% level. ** Significant at the 5% level. * Significant at the 10% level.

the sampled population on the whole (see Table 2). According to columns (3), (6) and (9), a one-year longer protogenesic interval results in a 3.9 percentage points higher probability of obtaining literacy, 5.5 percentage points higher probability of achieving a skilled occupation and a 0.16 point higher score on the occupational wealth scale for non-elite family offspring. These social-class differences may help explain why studies of contemporary high-income country populations have been unable to detect a strong quantity–quality trade-off (Black *et al.*, 2005; Angrist *et al.*, 2010).[48]

3.4. *Robustness: the Effect of the Protogenesic Interval on Child Quality*

To gauge the robustness of our results, we now consider the potential roles of extraordinarily long protogenesic intervals; the hereditary element of parental fecundity; additional control variables; and the use of alternative estimation methods.

Some couples had protogenesic intervals that are several years long. Although the time to conception can be rather extensive, as is well known from present-day populations, it is important to examine if our main results are driven by a few prolonged intervals representing unobserved heterogeneities or indeed measurement errors related to data recording. To this end, we use a Winsorised approach where protogenesic intervals that exceed three years and 40 weeks, corresponding to a time to conception of around three years (thus falling outside the 94th percentile) are reset to three years and 40 weeks. This way we retain useful information about low-fecundity families without giving them excessive leverage. Table 4, columns (1), (4) and (7), show that our baseline findings (Table 2) are robust to this re-specification. Our baseline findings are also robust to simply removing families with protogenesic intervals greater than three years and 40 weeks from the sample (Table 1, columns (2), (5) and (8)).

Fecundity might be heritable, i.e. there might be a correlation between hereditary elements of fecundity and offspring quality. In order to account for this, we control for the fecundity of family offspring by including dummy variables indicating if the offspring's protogenesic interval was below 40 weeks; between 40 weeks and one year; between one and two years; between two and three years; or over three years long. The background variable is unknown protogenesic interval.[49] Table 4, columns (3), (6) and (8), show that the results (Table 2) are robust and moreover that the length of the offspring's own protogenesic interval is not correlated with their human capital attainments, mirroring the conclusions from Table 1 above.

Other concerns that the protogenesic interval is correlated with the outcome variables for reasons not directly linked to fecundity can also be addressed. Newly-wed

[48] Our finding is also consistent with a theoretical argument put forth in Galor (2012), that unexpected births in wealthy populations, where intergenerational transfers take place, are more likely to reduce future intergenerational transfers to the children as opposed to reducing child quality. For parents wishing to transfer future income to their children, the optimal investment in their quality is where the rate of return on human capital equals the rate of return in physical capital, which in turn is constant from the viewpoint of the individual. The optimal adjustment to unexpected births will therefore be a reduction in intergenerational transfers, leaving investments in child quality unaffected.

[49] The protogenesic interval of offspring is known in 71% of the cases.

Table 4

The Effect of the Length of the Protogenesic Interval (PI) on Offspring Human Capital – Robustness to Alternative Protogenesic Interval Specifications

	Literacy			Skilled occupation			Occupational wealth		
	Winsorised (1)	No long PI's (2)	Controlling for own PI (3)	Winsorised (4)	No long PIs (5)	Controlling for Own PI (6)	Winsorised (7)	No long PIs (8)	Controlling for own PI (9)
Years to first birth (Winsorised)	0.054*** (0.018)			0.059*** (0.020)			0.156** (0.066)		
Years to first birth		0.065** (0.025)	0.033*** (0.011)		0.093*** (0.027)	0.039*** (0.013)		0.167* (0.089)	0.118*** (0.041)
PI of individual <40 weeks			−0.004 (0.037)			0.001 (0.046)			−0.277* (0.150)
PI of individual ≥40 weeks and <1 year			−0.008 (0.041)			−0.019 (0.051)			−0.067 (0.154)
PI of individual ≥1 year and <2 years			−0.035 (0.041)			0.017 (0.046)			−0.045 (0.155)
PI of individual ≥2 years and <3 years			0.088 (0.066)			−0.044 (0.075)			−0.266 (0.170)
PI of individual ≥3 years			0.032 (0.062)			−0.022 (0.069)			0.118 (0.260)
Baseline controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Parental skills	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Parental literacy	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Joint signif. of own PI dummies			0.583			0.969			0.293
R^2	0.227	0.215	0.227	0.331	0.333	0.330	0.354	0.352	0.360
No. of observations	1,248	1,180	1,248	652	616	652	686	647	686
No. of families	571	525	571	453	422	453	468	436	468

Notes. This table presents the results of a series of alternative OLS regression analyses of measures of human capital achievements on the time to first birth (i.e. protogenesic interval, abbreviated 'PI') in the family. In columns (1), (4) and (7), the protogenesic interval measure is winsorised at three years and 40 weeks (corresponding to a time to conception of around three years). In columns (2), (5) and (8), observations with a protogenesic interval longer than three years are excluded. In columns (3), (6) and (9), we control for the individual's own protogenesic interval (in the family that he or she starts) by including dummies for intervals of their own protogenesic interval as well as a dummy variable for unknown own protogenesic interval. All regressions account for parental marriage time-period fixed effects, maternal marriage age interval fixed effects, birth order fixed effects, and dummies indicating unknown information. The coefficient on a constant term is omitted from the table. Standard errors clustered on the family level are reported in parentheses. *** Significant at the 1% level. ** Significant at the 5% level. * Significant at the 10% level.

husbands could be engaged in economic activities, such as harvest work away from their home parish, involving their absence from the household following the wedding. Their absence would not only increase the protogenesic interval; it could also improve family income, thus helping to finance offspring human capital investments. We account for this by controlling for additional time-period fixed effects. Table C15 controls for seasonal (i.e. quarter-of-year) fixed effects relating to the parental marriage season and the season of the first birth. The table establishes that our results are robust to this re-specification.

Variation in wage rates may also have affected decisions about time spent working. More and harder work could have had an impact on the couple's sexual activities, through physical absence (or mere exhaustion), and this way affect not only the length of their protogenesic interval, but also the couple's investments in offspring human capital via an income channel. As reported in Table C16, our results are robust to accounting for this by controlling for the level of real wages in the 20-year period surrounding:

(*i*) the birth of the individual;
(*ii*) the marriage of the parents; and
(*iii*) the marriage of the offspring.

Temperature variation may influence agricultural work opportunities and thus again the demand for hard physical work. Furthermore, it may affect the protogenesic interval and offspring human capital in other ways. Table C17 shows that our results are robust to controlling for the average yearly temperature in the 20-year period again surrounding:

(*i*) the birth of each child;
(*ii*) the marriage of the parents; and
(*iii*) the marriage of the offspring.

Extraordinary living conditions, captured by extreme vital rates, may affect not only the length of the protogenesic interval (e.g. through undernourishment), but also offspring human capital investments via an income channel. We account for this in Table C18 by controlling for the average yearly birth and death rates in the 20-year period as above, i.e. surrounding:

(*i*) the birth of the individual;
(*ii*) the marriage of the parents; and
(*iii*) the marriage of the offspring.

Again, the results are robust.

A wide range of additional sensitivity checks are reported in the online Appendices. These establish that the main results are robust to accounting for the paternal age at marriage (Table C7); the birth year of offspring (Table C5); alternative offspring birth-order specifications (Table C10); alternative marriage age specifications (Table C19); maternal stoppage age, i.e. the age at which the mother had her last child (Table C19); the division of offspring by gender (Table C20); parental longevity (Table C21); and the season of birth of the first-born (Table C15). Lastly, our results are also robust to using a Heckit model to account for potential issues of sample selection (Table C22) or to using a logistic model with binary outcome variables instead (Table C13).

4. The Child Quantity–Quality Trade-off

Variation in fecundity between present-day couples may explain only a minor fraction of completed fertility, which is close to replacement. However, in historical populations where fertility rates were much higher on average, fecundity could have had a strong influence on family size. Below we examine the mechanism underlying the correlation between the protogenesic interval and offspring quality observed above. We establish using instrumental variable regression analysis that completed fertility, instrumented by the length of the protogenesic interval, has a statistically significant and negative effect on offspring human capital. This finding supports the notion that the link between parental fecundity and offspring human capital may have operated via a child quantity–quality trade-off.

The identifying assumption in our 2SLS analysis is that the length of the protogenesic interval, conditional on our control variables, affects our three measures of human capital only via family fertility. Our discussion of the determinants of the protogenesic interval in subsection 2.2 supports the assumption that the protogenesic interval can be used for this purpose. There, we argued that the most plausible violations of the exclusion restriction would link longer protogenesic intervals with lower offspring human capital investments. This would bias the estimated effect of completed fertility on offspring quality upwards, i.e. against observing a child quantity–quality trade-off.

We begin by examining the length of the protogenesic interval and family fertility. We show – theoretically as well as empirically – that there is a strongly statistically significant and positive effect of parental fecundity on completed fertility. We document that two additional years from the marriage to the first birth produces roughly one less surviving offspring.

4.1. *The Theoretical Effect of the Protogenesic Interval on Completed Fertility*

There are two key reasons to expect the length of the protogenesic interval to affect completed fertility. First, given the religious and social norms at the time, a longer protogenesic interval delayed the starting point of procreation and thus reduced the length of the remaining reproductive period. Second, if the length of the protogenesic interval reflects the probability to conceive within a given time frame, then longer protogenesic intervals should be positively correlated with the time-interval between subsequent births (called birth spacing). Either of these mechanisms are sufficient for the length of the protogenesic interval to instrument completed fertility and both are present in our data.

The compound mechanism can be formalised as follows. The reproductive period of a married couple remaining after the couple's first birth is $\rho - t$, where ρ denotes the marital reproductive period of a couple (i.e. the time span between marriage and sterility) and t denotes the time from the marriage to the first birth. Completed fertility is inversely related to the average birth-spacing interval, given by the function $s(t)$. If x

denotes the total number of births, then $x = (\rho - t)/s(t) + 1$. Next, we can approximate the average within-marriage birth interval by a linear function in t, $s(t) = c + \lambda t$, where c and λ are constants, hence obtaining the expression $x = (\rho - t)/(c + \lambda t) + 1$. Linearising this expression around some value of t, denoted by $\bar{t}$, yields that $x \approx \varphi_0 - \varphi_1 t$, where $\varphi_0 \equiv (\rho - \bar{t})/(c + \lambda\bar{t}) + \bar{t}(c + \lambda\rho)/(c + \lambda\bar{t})^2$ and $\varphi_1 \equiv (c + \lambda\rho)/(c + \lambda\bar{t})^2$.

If the protogenesic interval is not correlated with average birth intervals (a counterfactual but simplifying assumption), i.e. $\lambda = 0$, and if the average birth interval, c, is 2.5 years, an increase in the protogenesic interval of one year will result in 0.4 fewer children.[50] The higher the correlation between the protogenesic interval and average birth interval, the larger the absolute size of the effect. These mechanisms would imply that the protogenesic interval is a relevant instrument for completed fertility in historical populations.[51] The next subsection documents the link between the length of the protogenesic interval and subsequent intervals of family births.

4.2. *The Protogenesic Interval and Subsequent Birth Intervals*

Using a superset of the present data, Cinnirella *et al.* (2017) have shown that the length of the protogenesic interval was negatively correlated with the hazard of a birth in subsequent birth intervals (ibid., column 3 of Table 3). By restricting our sample used in Table 1 above to couples of more than one birth, we can replicate this result for present families using our usual control variables (Table C23 in online Appendix C). Unlike our findings in Table 1 above, which explored the determinants of the protogenesic interval, the time intervals between subsequent births are strongly and significantly correlated with parental socio-economic factors.[52] This is consistent with the sampled couples using the spacing between subsequent births as a means to adjust their realised fertility to their target family size. Having established a positive correlation between the length of the protogenesic interval and those of subsequent births, we now turn to estimating the effect on completed fertility of parental fecundity, measured by the protogenesic interval.

[50] We can compare this to a prediction accounting for empirical estimates of ρ, $\bar{t}$ and λ. Focusing on the sample of 729 families, we estimate these parameters as follows. Empirically, a lower bound of the point in time when sterility sets in is the date of the couple's final delivery. Using this as a proxy for the actual time of sterility, the average fertile period of mothers is $\rho = 16.14$ years. The average time to first birth across families is $\bar{t} = 1.58$ years. A simple regression of the family-level average birth interval length on the time to first birth, with robust standard errors, yields $\bar{c} = 2.55$ ($p < 0.001$) and $\bar{\lambda} = 0.07$ ($p = 0.016$). These numbers imply that $\overline{\varphi}_0 = 6.29$ and $\overline{\varphi}_1 = 0.52$. Indeed, a simple regression of completed fertility, as measured by the total number of births in the family, on the protogenesic interval (again using robust standard errors), provides similar estimates of ($\hat{\varphi}_0 = 7.01$ ($p < 0.001$)) and ($\hat{\varphi}_1 = 0.51$ ($p < 0.001$)). Furthermore, by comparing this prediction to that of 0.4 from the case where $\lambda = 0$, we find that around 21.6% of the compound effect of the protogenesic interval on completed family size is due to its effect on birth intervals.

[51] The protogenesic interval is a relevant instrument even if couples engage in stopping behaviour and if they incorporate a time buffer in their family planning, assuming that they choose their age at marriage so as to realise a desired family size. In that case, the protogenesic interval affects family size when it exceeds the length of the buffer. Such discrepancy between planned and actual fertility are presumably unrelated to the parental budget constraint. Hence, unplanned fertility changes may therefore affect the level of investments in child quality.

[52] Table C24 in online Appendix C shows that these results are robust to controlling for the maternal age at the beginning of each birth interval. The table also shows that maternal age at the beginning of the birth interval has a highly significant and negative effect on the hazard of birth.

Table 5
The Effect of the Length of the Protogenesic (PI) Interval on Completed Fertility

	Number of surviving siblings (>5 years)			
	Literacy sample	Skills sample	Wealth sample	Total sample
	(1)	(2)	(3)	(4)
Years to first birth	−0.450***	−0.485***	−0.520***	−0.467***
	(0.056)	(0.065)	(0.064)	(0.051)
Male	0.009	0.106	0.122	0.069
	(0.107)	(0.340)	(0.282)	(0.107)
Non-Sunday baptism	−0.092	−0.211	−0.225	−0.148
	(0.139)	(0.184)	(0.177)	(0.128)
Poor father	0.365	0.675**	0.724**	0.450*
	(0.281)	(0.330)	(0.316)	(0.259)
Skilled father	−0.260	−0.168	−0.124	−0.187
	(0.309)	(0.314)	(0.302)	(0.288)
Skilled mother	3.269*	4.092**	3.935**	3.075*
	(1.706)	(1.714)	(1.613)	(1.608)
Literate father	0.703**	0.794**	0.717**	0.672**
	(0.279)	(0.308)	(0.299)	(0.275)
Literate mother	−0.172	−0.229	−0.224	−0.103
	(0.288)	(0.345)	(0.336)	(0.281)
Agricultural location	0.347	0.433	0.413	0.291
	(0.277)	(0.307)	(0.305)	(0.261)
Industrial location	0.263	0.413	0.325	0.157
	(0.280)	(0.383)	(0.378)	(0.267)
Retail location	−0.528*	−0.381	−0.512**	−0.510**
	(0.301)	(0.261)	(0.256)	(0.222)
R^2	0.458	0.489	0.495	0.456
No. of observations	1,248	652	686	1,517
No. of families	571	453	468	729

Notes. This table presents the results of a series of OLS regression analyses of the number of surviving siblings on the time to first birth (i.e. protogenesic interval) in the family. All regressions account for parental marriage time-period fixed effects, maternal marriage age interval fixed effects, birth order fixed effects and dummies indicating unknown information. The coefficient on a constant term is omitted from the table. Standard errors clustered on the family level are reported in parentheses. *** Significant at the 1% level. ** Significant at the 5% level. * Significant at the 10% level.

4.3. *The Empirical Effect of the Protogenesic Interval on the Number of Siblings*

We examine the effect of the length of the protogenesic interval on completed fertility, as measured by the number of siblings of individuals, using the following regression model:

$$s_{ij} = \gamma_0 + \gamma_1 p_j + \mathbf{a}'_{ij}\boldsymbol{\gamma}_2 + \mathbf{b}'_j\boldsymbol{\gamma}_3 + \mu_{ij}, \tag{2}$$

where s_{ij} is the number of siblings in family j for individual i (common to all siblings); p_j is the protogenesic interval in family j; $\mathbf{a}_{ij}$ is a vector of individual-level control variables; $\mathbf{b}_j$ is a vector of family and parish-level control variables for family j; and finally μ_{ij} is an error term that is correlated within families.

The estimates, accounting for the usual control variables, are presented in Table 5. The Table shows a highly statistically significant and negative association between the protogenesic interval and completed fertility, as measured by the number of siblings. Depending on the sample used, two additional years of time from the marriage to the first birth reduces the number of siblings by roughly one child.[53] Slightly less than half of the variation in family fertility is explained by the length of the protogenesic interval and covariates. The covariates have largely the same partial effects regardless of the sample used.

In Table C25, we run similar regressions at the family level, meaning that we include one observation per family and exclude individual-specific control variables. While larger families weigh more in the individual-level regressions in Table 5, the estimates are rather similar when performed at the family level.

4.4. *Results*

Under the assumption of conditional exogeneity of the protogenesic interval, i.e. conditional on controlling for observed determinants, and in light of the effect of the protogenesic interval on completed fertility observed above, we can now estimate the effect of family fertility on offspring quality using instrumental variable regression. In the first stage of our 2SLS model, family fertility is instrumented by the length of the protogenesic interval, as given by (2) above. The second stage is given by the following regression equation:

$$h_{ij} = \delta_0 + \delta_1 \hat{s}_{ij} + \mathbf{a}'_{ij}\boldsymbol{\delta}_2 + \mathbf{b}'_j\boldsymbol{\delta}_3 + \nu_{ij}, \tag{3}$$

where h_{ij} is a measure of the human capital of individual i in family j; $\hat{s}_{ij}$ is the predicted number of siblings of individual i in family j resulting from the estimation of (2); $\mathbf{a}_{ij}$ is a vector of individual-level control variables; $\mathbf{b}_j$ is a vector of family and parish-level control variables for family j; and finally ν_{ij} is an error term that is correlated within families.

Table 6 shows a highly statistically significant and negative association between completed fertility, instrumented by the protogenesic interval, and offspring human capital. This result appears regardless of the measure of human capital used and both before and after controlling for a wide range of important covariates including parental socioeconomic characteristics.[54] Our specifications, including all baseline control variables, show that a family size of one additional surviving offspring decreases the offspring's probabilities of achieving literacy by 7.1 percentage points (column (3)) and their probabilities of achieving a skilled occupation by 7.9 percentage points (column (6)). Furthermore, it decreases occupational wealth by 0.22 points on the seven-point scale (column

[53] Corresponding to the samples use in columns (1)–(3) of Table 2 above, column (1) of Table 5 shows that one additional year of time to first birth decreases the number of siblings by 0.45 surviving children on average, while columns (2) and (3) suggest 0.49 and 0.52 fewer surviving children. When using a combined sample of those offspring included in columns (1)–(3) of Table 2, column (4) of Table 5 shows that an additional year to first birth decreases the number of siblings by 0.47 surviving children on average.

[54] The protogenesic interval is a strong instrument for completed fertility, as witnessed by the Wald F-test statistics based on the Kleibergen–Paap *rk* statistic (Kleibergen and Paap, 2006), which always exceed 53 and so are well above the rule-of-thumb-value of 10 (Staiger and Stock, 1997; see also Stock and Yogo, 2005).

Table 6

Instrumental Variables Regressions: the Effect of the Number of Siblings on Human Capital

	Literacy			Skilled occupation			Occupational wealth		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Surviving siblings (> 5 years)	−0.067**	−0.068***	−0.071***	−0.084***	−0.082***	−0.079***	−0.230***	−0.237***	−0.217***
	(0.026)	(0.026)	(0.025)	(0.031)	(0.029)	(0.028)	(0.085)	(0.083)	(0.081)
Baseline controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Parental skills	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Parental literacy	No	No	Yes	No	No	Yes	No	No	Yes
F (Kleibergen–Paap)	68.8	67.7	64.6	57.8	53.4	56.4	65.5	62.4	66.6
Anderson–Rubin *F* stat. p-value	0.010	0.011	0.004	0.004	0.003	0.003	0.005	0.003	0.006
Endogeneity test p-value	0.009	0.011	0.011	0.008	0.008	0.009	0.005	0.005	0.011
Plausibly exogenous p-value	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%	<1%
No. of observations	1,248	1,248	1,248	652	652	652	686	686	686
No. of families	571	571	571	453	453	453	468	468	468

Notes. This table presents the results of a series of 2SLS regression analyses of measures of human capital achievements on the number of surviving siblings in the family, instrumented by the time to first birth (i.e. protogenesic interval). All regressions account for parental marriage time-period fixed effects, maternal marriage age interval fixed effects, birth order fixed effects and dummies indicating unknown information. The 'plausibly exogenous p-value' is based on the union of confidence interval approach in Conley *et al.* (2012) assuming a direct effect of the protogenesic interval on offspring human capital that is ±10% of the estimated effect of the number of surviving siblings in the corresponding column. The coefficient on a constant term is omitted from the table. Standard errors clustered on the family level are reported in parentheses. *** Significant at the 1% level. ** Significant at the 5% level. * Significant at the 10% level.

(9)). These findings strongly support the existence of a child quantity–quality trade-off among the sampled families.

4.5. *Quantitative Exploration of the Magnitudes of Our Estimates*

Thanks to numbers provided in Humphries (2010) and Minns and Wallis (2013) concerning the costs of education in the past, along with a basic budget model and a few simplifying assumptions, we can compare the magnitude of our findings to the effect implied by the simple budget model.

According to Minns and Wallis (2013), the usual premium paid by parents for an apprenticeship in a medium-skilled profession at the time ranged from around £10 to £15 per child. One of the main advantages of apprenticeship training, especially for poor families, was that once the initial indenture fee was paid the apprenticeship normally allowed the offspring to finance the rest of their training themselves by working for their master. In addition, parents endured the cost of elementary schooling. At a fee of six pence per week and 45 weeks of schooling per year, schooling expenses according to Humphries (2010), came to one pound, two shillings and six pence a year per child.

Meanwhile, the schooling fee was dwarfed by the opportunity costs of schooling one's children. Child labour during this period, again according to Humphries (2010), paid around two shillings per week, meaning that the household income foregone by sending a child to school rather than to work for 45 weeks a year came to some £36 per child – a considerable amount of extra income for a poor family. Hence, a crude estimate of the total costs for a child to obtain a skilled profession, including elementary schooling and apprenticeship fees as well as the loss of household income, added up to some £58 per child or almost five years of wages of an unskilled worker.

Next, in order to estimate the cost of childrearing, we consider the costs of a standardised historical consumption basket proposed in Allen (2009). Allen's basket contains a line of basic commodities reckoned to have been consumed by an average adult at the time. The basket includes food, drink, clothing, heating and housing in amounts attuned to fit the consumption of an individual eating 2,500 calories per day. Allen also provides the historical prices necessary to compute the costs of the basket each year during the relevant years.[55]

However, because Allen's basket concerns an adult individual, we need an estimate of the number of calories consumed by a child until its 15th birthday, when children usually left home. According to the Food and Agricultural Organisation of the United Nations (FAO),[56] a one-year-old child needs about 30% of the caloric intake of an adult; a two-year-old needs 36%; a three-year-old needs 43%; and so on, adding about 10 percentage points more calories for each year until the child reaches the age of 15. Using the relevant historical prices of each item contained in Allen's basket, it is possible, by scaling the child's consumption according to the FAO caloric intake recommendations, to compute the total costs of rearing a child from birth to age 15. Following this procedure, the total childrearing expenses for a 15-year old child born in 1700 came to £42.

[55] This data can be found at http://www.nuffield.ox.ac.uk/People/sites/Allen/SiteAssets/Lists/Biography%20Sections/EditForm/london.xls.

[56] This data can be found at http://www.fao.org/docrep/003/aa040e/AA040E07.htm.

Based on these estimates, we can now consider how much extra education an average family could afford if the average family size decreased by one child. One child costs £42 in terms of basic consumption goods. An educated child costs an extra £58. An uneducated working child, conversely, would bring in £36. The average family size was close to five children (i.e. total births). Among those in our sample who had their occupation recorded, 68%, or 3.4 children, were skilled (see Table A.3). Assuming, as an approximation, that this share is representative of surviving children, the expected cost of a surviving child was therefore 0.68(£42 + £58) + 0.32(£42 − £36) = £69.92. If s denotes the share of children surviving, c denotes the expected cost of a surviving child and q denotes the proportion of costs of a non-surviving child compared to the costs of a surviving child, then the expected costs of a child is $c[s + (1 - s)q]$. Around 56% of children survived to age 15. Assuming that the expected cost of children who survived to age 15 was half that of those who did survive, an average family could then expect to save around £54.50 if it had one surviving child less. If this windfall gain was spent entirely on child education, then it would pay for $54.5/58 = 0.94$ more educated children. One child less therefore meant that 3.66 out of four children would obtain education on average. In other words, the chances of being educated would rise by 23.5 percentage points. In light of the uncertainties involved in this calculation, not to mention the fact that parents might have spent windfall gain on other consumption items as well, our empirical finding of a 7.9 percentage points increased likelihood of being skilled is certainly plausible.

4.6. *Robustness Concerning the Effect of Child Quantity on Child Quality*

Analogously to subsection 3.4, we can gauge the robustness of our findings by conducting a number of sensitivity checks. These include testing for sample selection bias and relaxing the assumption about strict exogeneity of the instrument.

First, Table 7, columns (1), (4), (7), (9), (11) and (14) show that our findings are robust to Winsorising the instrument by reducing the value of the protogenesic interval variable whenever it exceeds three years and 40 weeks, corresponding to a time to conception of around three years and thus falling outside of the 94th percentile, to three years and 40 weeks. Our findings are also robust to excluding families with intervals that are more than three years and 40 weeks long (Table 7, columns (2), (7) and (12)). Moreover, by confining the sample to completed marriages, i.e. marriages in which both spouses survived in marriage until the wife turned 50, we mitigate the possibility of permanent migration, helping us to steer clear of births occurring outside the sampled parishes. However, it was not unusual for couples to migrate to an unobserved parish temporarily (Souden, 1984). A few years of absence might mean that a migrating couple would conceive (and thus baptise) a child in their interim location. This would appear in the data in the form of an extended birth-spacing interval and the resulting child would go unobserved. To address this issue, we can impute an extra birth into all birth intervals that are over three years' long. This (probably counterfactually) increases the average family size by 1.3 children. The revised estimates are reported in Table 7, columns (5), (10) and (15), and establish that our baseline results are robust.

As shown in Table 7, columns (3), (6) and (8), the baseline instrumental variable results (Table 6) are robust to accounting for a heritable component of

Table 7

Robustness to Alternative IV Specifications

	Literacy				
	Winsorised (1)	No long PIs (2)	Controlling for own PI (3)	Winsorised PI and imputed siblings (4)	Imputed siblings (all intervals) (5)
Surviving siblings (> 5 years)	−0.093*** (0.033)	−0.152** (0.072)	−0.073*** (0.025)		
Surviving siblings (with imputed siblings, first interval)				−0.186** (0.081)	
Surviving siblings (with imputed siblings, any interval)					−0.073*** (0.026)
Years to first birth (Winsorised)					
PI of individual <40 weeks			0.016 (0.039)		
PI of individual ≥40 weeks and <1 year			0.010 (0.044)		
PI of individual ≥1 year and <2 years			−0.036 (0.041)		
PI of individual ≥2 years and <3 years			0.098 (0.065)		
PI of individual ≥3 years			0.071 (0.065)		
Baseline controls	Yes	Yes	Yes	Yes	Yes
Parental skills	Yes	Yes	Yes	Yes	Yes
Parental literacy	Yes	Yes	Yes	Yes	Yes
F (Kleibergen–Paap)	36.4	11.8	62.0	9.0	44.0
Anderson–Rubin *F* stat. p-value	0.003	0.010	0.004	0.003	0.004
Endogeneity test p-value	0.005	0.012	0.010	0.003	0.016
Plausibly exogenous p-value	<1%	<5%	<1%	<1%	<1%
No. of observations	1,248	1,180	1,248	1,248	1,248
No. of families	571	525	571	571	571
	Skilled occupation				
	Winsorised (6)	No long PIs (7)	Controlling for own PI (8)	Winsorised PI and imputed siblings (9)	Imputed siblings (all intervals) (10)
Surviving siblings (> 5 years)	−0.097*** (0.035)	−0.247** (0.109)	−0.078*** (0.028)		
Surviving siblings (with imputed siblings, first interval)				−0.171** (0.072)	
Surviving siblings (with imputed siblings, any interval)					−0.086*** (0.033)
Years to first birth (Winsorised)					
PI of individual <40 weeks			0.004 (0.046)		
PI of individual ≥40 weeks and <1 year			−0.050 (0.052)		
PI of individual ≥1 year and <2 years			0.006 (0.046)		
PI of individual ≥2 years and <3 years			−0.034 (0.077)		
PI of individual ≥3 years			−0.025 (0.069)		
Baseline controls	Yes	Yes	Yes	Yes	Yes
Parental skills	Yes	Yes	Yes	Yes	Yes
Parental literacy	Yes	Yes	Yes	Yes	Yes
F (Kleibergen–Paap)	37.3	6.9	58.4	11.9	32.1

Table 7

(*Continued*)

	Skilled occupation				
	Winsorised (6)	No long PIs (7)	Controlling for own PI (8)	Winsorised PI and imputed siblings (9)	Imputed siblings (all intervals) (10)
Anderson–Rubin *F* stat. p-value	0.002	0.001	0.003	0.002	0.003
Endogeneity test p-value	0.004	0.001	0.009	0.003	0.008
Plausibly exogenous p-value	<1%	<5%	<1%	<1%	<1%
No. of observations	652	616	652	652	652
No. of families	453	422	453	453	453

	Occupational wealth				
	Winsorised (11)	No long PIs (12)	Controlling for own PI (13)	Winsorised PI and imputed siblings (14)	Imputed siblings (all intervals) (15)
Surviving siblings (> 5 years)	−0.239** (0.102)	−0.410* (0.247)	−0.224*** (0.081)		
Surviving siblings (with imputed siblings, first interval)				−0.407** (0.190)	
Surviving siblings (with imputed siblings, any interval)					−0.224*** (0.085)
Years to first birth (Winsorised)					
PI of individual <40 weeks			−0.267* (0.145)		
PI of individual ≥40 weeks and <1 year			−0.146 (0.159)		
PI of individual ≥1 year and <2 years			−0.078 (0.154)		
PI of individual ≥2 years and <3 years			−0.269 (0.180)		
PI of individual ≥3 years			(0.259)		
	Yes	Yes	Yes	Yes	Yes
Parental skills	Yes	Yes	Yes	Yes	Yes
Parental literacy	Yes	Yes	Yes	Yes	Yes
F (Kleibergen–Paap)	44.6	8.8	69.7	15.3	40.7
Anderson–Rubin *F* stat. p-value	0.018	0.061	0.004	0.018	0.006
Endogeneity test p-value	0.022	0.065	0.008	0.018	0.011
Plausibly exogenous p-value	<1%	<10%	<1%	<5%	<1%
No. of observations	686	647	686	686	686
No. of families	468	436	468	468	468

Notes. This table presents the results of a series of alternative 2SLS regression analyses of measures of human capital achievements on the number of surviving siblings in the family, instrumented by the time to first birth (i.e. protogenesic interval, abbreviated 'PI'). In columns (1), (6) and (11), we have Winsorised the protogenesic interval at three years and 40 weeks (corresponding to a time to conception of around three years). In columns (2), (7), and (12), we exclude observations for families with a protogenesic interval longer than three years and 40 weeks (corresponding to a time to conception of around three years). In columns (3), (8) and (13), we control for the individual's own protogenesic interval (in the family that he or she starts) by including dummies for intervals of their own protogenesic interval as well as a dummy variable for unknown own protogenesic interval. In column (4), (9), and (14), we impute an extra sibling for those families in which the protogenesic interval exceeds three years. In columns (5), (10) and (15), we impute an extra sibling for each birth interval above three years. All regressions account for parental marriage time period, maternal marriage age, and dummies indicating unknown information. The 'plausibly exogenous p-value' is based on the union of confidence interval approach in Conley *et al.* (2012) assuming a direct effect of the protogenesic interval on offspring human capital that is ±10% of the estimated effect of the number of surviving siblings in the corresponding column. The coeffcient on a constant term is omitted from the table. Standard errors clustered on the family level are reported in parentheses. *** Significant at the 1% level. ** Significant at the 5% level. * Significant at the 10% level.

fecundity as proxied by the offspring's own protogenesic interval. Furthermore, as shown in Table C8 the results are also robust to controlling for the paternal marriage age. We also performed a Heckit IV analysis (Table C26 in online Appendix C) and found no indication that our results were driven by issues of sample selection.

Our key identifying assumption is that marriage marked the intention to start a family. This implies that couples did not deliberately engage in behaviour that would delay their first birth with the intention of having fewer but higher quality offspring. Our evidence presented in subsections 2.2.3–2.2.4 suggests an overall absence of any systematic delaying behaviour. Nevertheless, it would be presumptuous to completely rule out the possibility that at least some couples acted this way, or that other factors affecting both the protogenesic interval and offspring quality were entirely absent. In other words, the protogenesic interval may be a so-called imperfectly exogenous variable. To deal with this, we employ a methodology developed by Conley *et al.* (2012), which relaxes the assumption of perfect exogeneity and in our case allows for a direct effect of the protogenesic interval on offspring quality. The resulting significance levels are found in the rows labelled 'plausibly exogenous p-value' in Tables 6 and 7, as well as in Tables C8 and C26 in online Appendix C. By assuming a direct effect of the protogenesic interval on offspring human capital, which is $\pm 10\%$ of the estimated effect of the number of surviving siblings, we find that our qualitative instrumental-variable findings are robust to this relaxation of the assumption about exogeneity.

5. Conclusion

The demographic transition and the concurrent rise in global levels of human capital and living standards over the past two centuries has transformed human societies. We proposed and tested the hypothesis that human fecundity, i.e. the individual and variable capacity to reproduce, played a significant role in the formation of human capital in the pre-industrial world. We find that individuals with longer protogenesic intervals had fewer children with higher levels of human capital, indicating that fecundity had a positive effect on family size and a negative effect on offspring quality. Our analysis established that the effect on human capital was weaker for members of the socio-economic elite, who supposedly was better able to offset the cost of additional children by raising total expenditures on offspring human capital. We also developed a novel empirical strategy for estimating the effects of family size on various outcomes and used it to document the existence of a trade-off between child quantity and child quality in England during the industrial revolution.

Our findings provide empirical support to one of the key mechanisms in the so-called unified growth theories that attempt to explain economic growth and demographic dynamics over the very long run (Galor, 2011). These theories typically ascribe the historical fertility decline in Western Europe to a growing demand for education, stimulated by technological progress during the transition to modern economic growth. According to the theories, parents reduced their fertility in order to afford better educated children. Our analysis also lends support to evolutionary growth theories, which hypothesise that individuals with an innate bias towards the quality rather than the quantity of children improved the income potential and hence the reproductive success of their lineage. If our findings are more widely applicable, then, consistent with theory, an effect of biologically determined influences on human capital formation could have gradually expanded the representation of economic-growth enhancing traits in the population, contributing to the long-term process of economic development as well as the demographic transition (Galor and Moav, 2002; Galor and Klemp, 2016).

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Additional Supporting Information may be found in the online version of this article:

Appendix A. Additional Text.
Appendix B. Additional Figures.
Appendix C. Additional Tables.
Data S1.

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